VZ Librae: an Eclipsing Contact Binary in a Ternary System

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Abstract Time series of the eclipsing contact binary VZ Lib are reported and times of minima (ToM) of the eclipses are measured. This system has a third component. From the O–C analysis of the observed ToM and of those in the literature, the orbital parameters of the third body can be derived: the orbital period is 34.8 years and the inclination is 11.5°.

1. Introduction

VZ Librae is an eclipsing contact binary system with a period of 8.6 hours (W UMa type) in a triple system. The third star was observed spectroscopically by Lu *et al.* (2001) with a relative flux of 0.2. Zola *et al.* (2004) fitted the light curve with a relative flux of 0.048 (in *V*), and D'Angelo *et al.* (2006) observed by spectroscopy a flux of about the same value (0.045). Ruciński *et al.* (2007) attempted to resolve the third star with adaptive optics (resolution down to 0.07") but they came up with a negative result.

The parallax of VZ Lib is 4.92±1.96m", as measured by Hipparcos (Perryman *et al.* 1997). The distance is then 203±81pc. According to Szalai *et al.* (2007) the distance is 171±8 pc.

2. Observations

I observed VZ Lib with a 203mm Schmidt-Cassegrain telescope, Johnson *V* and *B* filters, and a SBIG ST7E camera (KAF401E CCD) at my amateur MBCAA Observatory. In 2007, most of the observations were done by observing with the *V* and *B* filters. In 2008–2009, only the *V* filter was used. The exposure durations were 60 seconds for the *V* images and 200 seconds for the *B* images:

- 2007: 4 sessions, 116 *V* images, 62 *B* images;
- 2008: 7 sessions, 799 *V* images;
- 2009: 3 sessions, 363 *V* images.

For the differential photometry, the comparison star used was TYC 6184-1101-1 with *B* = 9.944 and *V* = 9.450 (computed from the Tycho magnitudes owing to Mamajek *et al.* 2002, 2006). All the data are in the AAVSO International Database, observer code BZU. An example of a light curve is given in Figure 1.

The color may be considered as constant, with *B–V* = 0.617 ± 0.022 (transformed).

3. Modeling the eclipsing binary with BINARY MAKER 3

The 2008 measurements were folded with the published period of the contact binary (the 2007 and 2009 measurements were not included as the period seems to vary, see below). I fit the resulting phase plot with BINARY MAKER 3, a software program for the study of binary stars (Bradstreet and Steelman 2004).

With the parameters of Zola *et al.* (2004), I achieved a good fit to my data (and also those from the ROTSE-1 (Woźniak *et al.* 2004) and ASAS-3 (Pojmański 2002) surveys, see below). The phase plot with the synthetic light curve is in Figure 2. With the parameters of Szalai *et al.* (2007) I also achieved a good fit although they are somewhat different of those of Zola *et al.* (2004), e.g. third light (as a fraction of the system light flux) of 0.2 instead of 0.043, mass ratio of 0.33 instead of 0.255.

I observed eight minima and I timed them by fitting with the synthetic light curve. These times of minima are, along with twenty-five others from the literature, listed in Table 1.

The ROTSE-I/NSVS survey observed VZ Lib in 1999 and 2000. These measurements were folded with the derived period and two phase plots were obtained for the two seasons. I fitted them by hand with the BINARY MAKER 3 synthetic light curve and I obtain two times of minima. These ToM are then not determined from the observation of individual minima, but each of them is rather an average over the season. Figure 3 is an example of a phase plot with the 1999 observations. I did the same with the ASAS-3 survey (Pojmański 2002) to obtain five ToM for 2001–2004. All these ToM are listed in Table 2.

4. Analysis

I derived the ephemeris for the eclipses of the contact binary and the orbital parameters of the third body the following way:

- Section 5, below: I obtained a preliminary ephemeris for the eclipses by fitting the ToM with a linear function. I then derived an O–C diagram with the difference between the observations and this preliminary ephemeris;

- Section 6, below: I fitted the O–C diagram with the equations from Kepler's laws, obtaining a preliminary determination of the orbital parameters;

- Section 7, below: I corrected the observed ToM with the light-travel times. A new ephemeris for the eclipses was then obtained, and a new O–C diagram was derived, the same way as in Section 5.

I then fitted the new O–C diagram with Kepler's equations, obtaining a new determination of the orbital parameters, the same as in Section 6.

I obtained a final ephemeris for the eclipses (with the light-travel time effect removed) and a final determination of the orbital parameters for the third star iteratively by repeating the above several times.

5. Preliminary determination of the ephemeris for the eclipses (iteration 0)

I made a preliminary determination of the period and origin of eclipses of the contact binary from the times of minima of Table 1 the following way:

- I started from my 2008 observations, using an already published period for the cycle count, determining the ephemeris with a least squares method;
- I included the ToM from 2007 and 2009, obtaining a more accurate ephemeris;
- I continued with more ToM, always checking that there is no cycle ambiguity, obtaining smaller and smaller uncertainties;
- When I used all the data of Table 1, I gave some heavy weight to the lone 1940 measurement (and a weight of 1 to all the others).

The resulting preliminary ephemeris for the secondary minima is then:

$$\mathrm{HJD(E)} = 2454644.4323(10) + 0.35825792(10)\,\mathrm{E} \tag{1}$$

where the uncertainties also reflect different values of the 1940 weight.

The difference between the observed ToM (of Table 1 and of Table 2) and the above ephemeris is the O–C diagram of Figure 4.

6. Preliminary determination of the parameters of the third body (iteration 0)

The O–C diagram of Figure 4 shows variations with an amplitude of about 50 minutes. This is considered to arise from the light-travel time effect in the ternary system. The period appears to be about 33 years.

The light-travel time effect can be computed from Kepler's laws. When the eclipse minima are observed on Earth, they are delayed by:

$$\mathrm{LTT} = \frac{-r\,sin(i)}{c}\sin(\phi+\omega) + \frac{a\,e\,sin(i)}{c}\sin(\omega) \tag{2}$$

where ω is the periastron longitude (from the node line), *a* the semi-major axis, *i* the inclination, *e* the eccentricity, *c* the velocity of light, and:

$$r = \frac{a(1-e^2)}{1+e\,cos(\phi)} \tag{3}$$

$$\phi = 2\,atan\left[\sqrt{\frac{1+e}{1-e}}\;tan\left[\pi\frac{t-t_0}{P}+\frac{\sqrt{1-e^2}}{2(1+e\,cos(\phi))}\,e\,sin(\phi)\right]\right] \quad (4)$$

with t the time, t_0 the time of passage at periastron and P the period.

I fitted the O–C diagram with LTT using a "Monte Carlo" algorithm. For the five parameters to be determined, I considered the ranges of possible values given in Table 3.

The Monte Carlo algorithm works the following way:

- 1,000,000 sets of the five parameters are generated randomly, within their respective ranges;
- the set that gives the best fit to the observations of Table 1 and Table 2 is retained. To determine how good a fit is, the uncertainties on the O–C measurements are used as weights: the larger the uncertainty, the less the measurement is taken into account;
- the above process is repeated ten times so that ten sets of best fitting parameters are obtained;
- the adopted values are the averages of the ten sets and, as the uncertainties, the standard deviations.

The resulting parameters are given in Table 4 and the O–C diagram with the fit is the solid line in Figure 4.

7. Iterative determination of the ephemeris and of the orbital parameters

I used the above determination of the orbital parameters to correct the observed times of minima for the light-travel times. A new ephemeris for the period of the contact binary was then obtained the same way as in Section 5. A new O–C diagram was also derived and a new Kepler's solution was obtained the same way as in Section 6.

The above process was repeated a few times. It converged quickly. It also became independent of the weight given to the 1940 measurement (this can be set to 1). The resulting ephemeris for the secondary eclipses of the contact binary (with the light-travel time effect removed) is:

$$HJD(E) = 2454644.4321(7) + 0.35825789(2)\,E \quad (5)$$

and the orbital parameters of the third body are in Table 5, with the O–C diagram shown in Figures 5 and 6.

8. Discussion

Qian *et al.* (2008) fitted the O–C diagram with a sinusoidal function. Their Figure 2 shows a period of about 35,000 cycles, which looks about the same as the period of 34.8 years I obtained. However, they reported a period half that, 17.1 years, with which my results are not in agreement.

The period *P* is connected to the total mass *M* and to the semi-major axis *a* through:

$$P = \frac{2\,\pi\,a^{1.5}}{\sqrt{GM}} \tag{6}$$

where *G* is the gravitational constant.

According to Zola *et al.* (2004) the mass of the contact binary is: $M_1 + M_2 = 1.480 \pm 0.068 + 0.378 \pm 0.034 = 1.858 \pm 0.102\,M_\odot$.

The mass M_3 of the third star can then be computed as a function of the inclination and the result is shown Figure 7. M_3 is sharply dependent upon the inclination, allowing *i* to be constrained to i = 11.5° with an uncertainty of about 1°.

According to Szalai *et al.* (2007) the mass of the contact binary is $M_1 + M_2 = 1.06 + 0.35 = 1.41\ M_\odot$, and of the third star is $M_3 = 0.90$.

With my parameters, the value of the inclination is in the same range as above.

The semi-major axis is then a = 15 AU, which corresponds to an angular distance of 0.09".

The orbital plane of the eclipsing contact binary is not at all in the orbital plane of the third star. This suggests that the contact binary did not form along with the ternary system. The fairly elongated orbit (e = 0.30) may not favor a common origin either.

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Zola, S., *et al.* 2004, *Acta Astron.*, **54**, 299.

Table 1. VZ Lib times of minima.

Date	*ToM*	*Uncertainty*	*I/II*	*Reference*
1940	2429645.010		I	Tsessevich (1954), reported by Claria and Lapasset (1981)
1980	2444366.7339		II	Claria and Lapasset (1981)
1980	2444408.6509		II	Claria and Lapasset (1981)
1981	2444698.8448		II	Claria and Lapasset (1981)
1981	2444787.5154		I	Claria and Lapasset (1981)
1981	2444788.5901		I	Claria and Lapasset (1981)
1981	2444789.6654		I	Claria and Lapasset (1981)
1981	2444790.5608		II	Claria and Lapasset (1981)
1991	2448500.3370	0.0001	II	Perryman *et al.* (1997)
2003	2452725.4345	0.0001	I	Qian *et al.* (2008)
2003	2452725.6135	0.0002	II	Qian *et al.* (2008)
2003	2452726.5097	0.0001	I	Qian *et al.* (2008)
2003	2452727.4050	0.0002	II	Qian *et al.* (2008)
2003	2452727.4047		II	Zola *et al.* (2004)
2003	2452727.5847	0.0003	I	Qian *et al.* (2008)
2003	2452730.6304	0.0004	II	Qian *et al.* (2008)
2004	2453189.0102		I	Szalai *et al.* (2007)
2005	2453438.8952	0.0003	II	Krajci (2006)
2005	2453450.5387	0.0004	I	Zejda *et al.* (2006)
2005	2453509.8297	0.0006	II	Ogłoza *et al.* (2008)
2005	2453511.6204	0.0010	II	Ogłoza *et al.* (2008)
2005	2453511.7985	0.0021	I	Ogłoza *et al.* (2008)
2005	2453517.7113	0.0013	II	Ogłoza *et al.* (2008)

(Table 1 continued on following page)

Table 1. VZ Lib times of minima, continued.

Date	ToM	Uncertainty	I/II	Reference
2007	2454164.3650	0.0005	II	Qian *et al.* (2008)
2007	2454233.502	0.0015	II	This paper
2007	2454301.3905	0.0020	I	This paper
2008	2454539.6335	0.0005	I	This paper
2008	2454644.4240	0.0010	II	This paper
2008	2454646.3950	0.0003	I	This paper
2008	2454656.4265	0.0015	I	This paper
2008	2454667.3522	0.0001	II	Samolyk (2009)
2009	2454894.6686	0.0010	I	This paper
2009	2454971.5140	0.0010	II	This paper

Table 2. VZ Lib times of minima (averages) from the ROTSE-1 and ASAS-3 surveys.

Date	ToM	Uncertainty	I/II	Survey
1999	2451314.615	0.002	I	ROTSE
2000	2451615.201	0.002	I	ROTSE
2001	2452034.711	0.003	I	ASAS
2002	2452475.012	0.002	I	ASAS
2003	2452773.799	0.002	I	ASAS
2004	2453132.763	0.003	I	ASAS
2005	2453521.475	0.002	I	ASAS

Table 3. VZ Lib ranges of values for the ternary orbital parameters.

Parameter	Range
a *sin*(i) (AU)	-3.5 ± 1.0
e	0.3 ± 0.3
ω(°)	180 ± 180
P (yr)	33 ± 5
t_0 (HJD)	2454900 ± 200

Table 4. VZ Lib first result (iteration 0) for the determination of the ternary orbital parameters.

Parameter (iteration 0)	*Value (iteration 0)*	*Uncertainty*
a *sin*(i) (AU)	3.05	0.03
e	0.305	0.005
ω(°)	90.6	0.5
P (yr)	35.1	0.2
t_0 (HJD)	2454977	15

Table 5. VZ Lib ternary orbital parameters.

Parameter	*Value*	*Uncertainty*
a *sin*(i) (AU)	3.026	0.019
e	0.308	0.007
ω(°)	91.0	0.8
P (yr)	34.78	0.26
t_0 (HJD)	2454979 (27 May 2009)	18

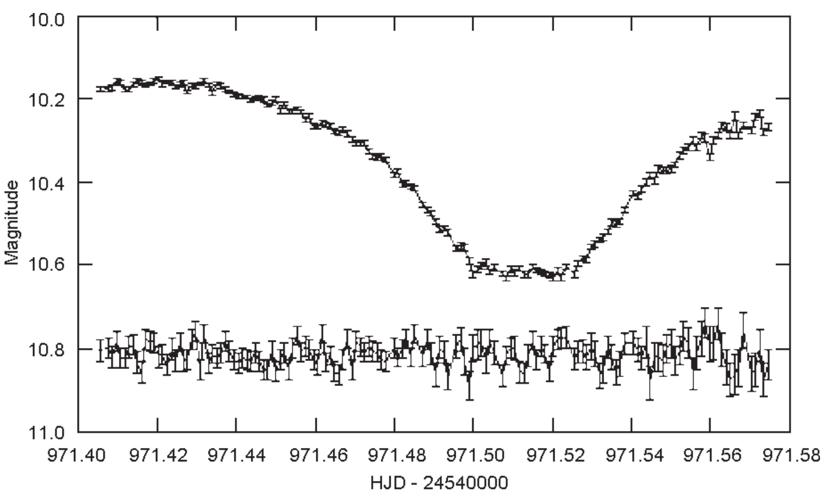

Figure 1. An example of a VZ Lib light curve, from the session of 19 May 2009. The check star (GSC6184-00385) measurements are shifted by –1.8 magnitude. The error bars are ± the 1-sigma statistical uncertainties. The eclipse is a secondary one (II), note the flat bottom.

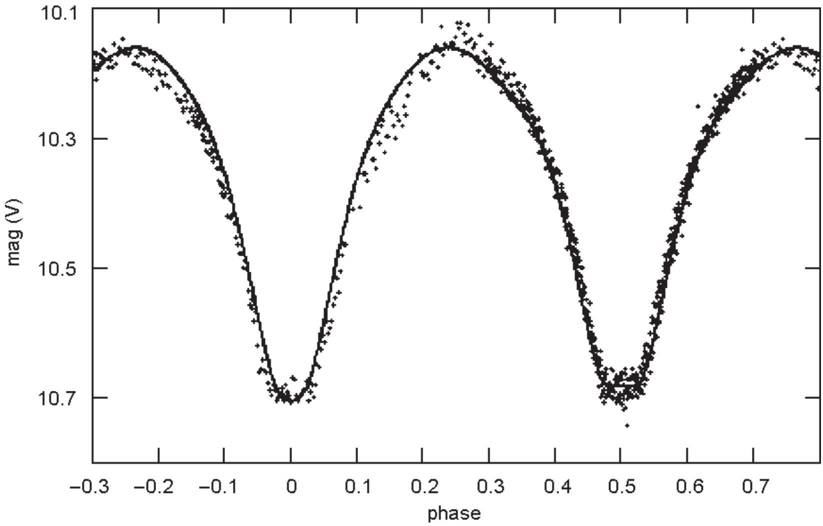

Figure 2. Phase plot of the author's 2008 observations of VZ Lib along with the synthetic light curve. Note the variability at the secondary eclipse, and also in Figure 3.

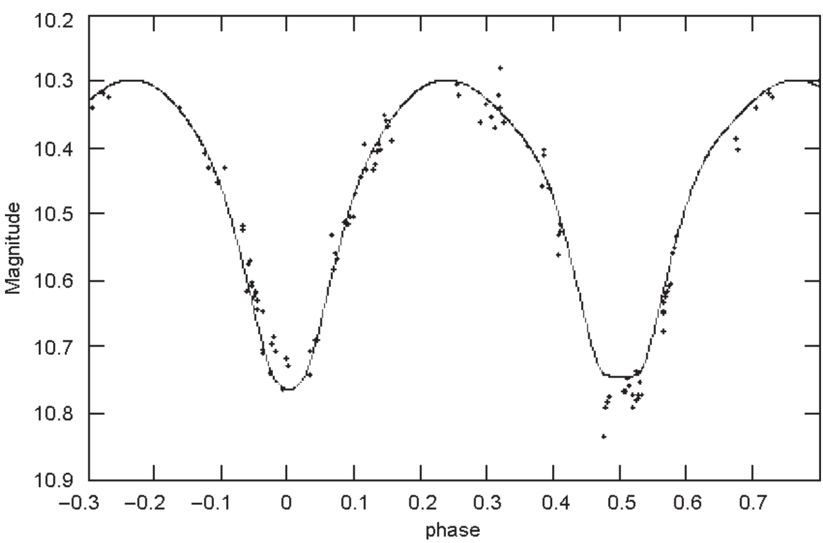

Figure 3. Phase plot of the 1999 ROTSE-1 observations of VZ Lib along with the synthetic light curve.

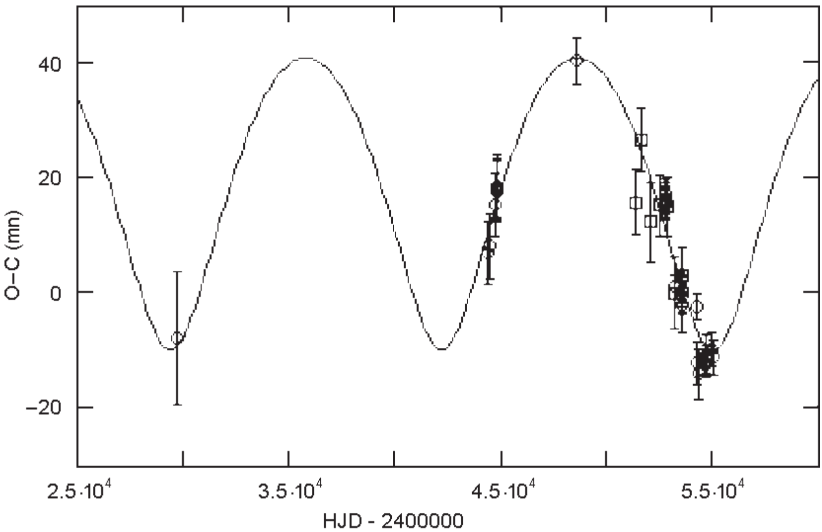

Figure 4. O–C diagram (1940–2009) for VZ Lib from the first result (iteration 0) for the determination of the primary parameters. Circles, individual minima; Squares, average minima from ROTSE-1 and ASAS-3; Solid line, light- travel time calculation.

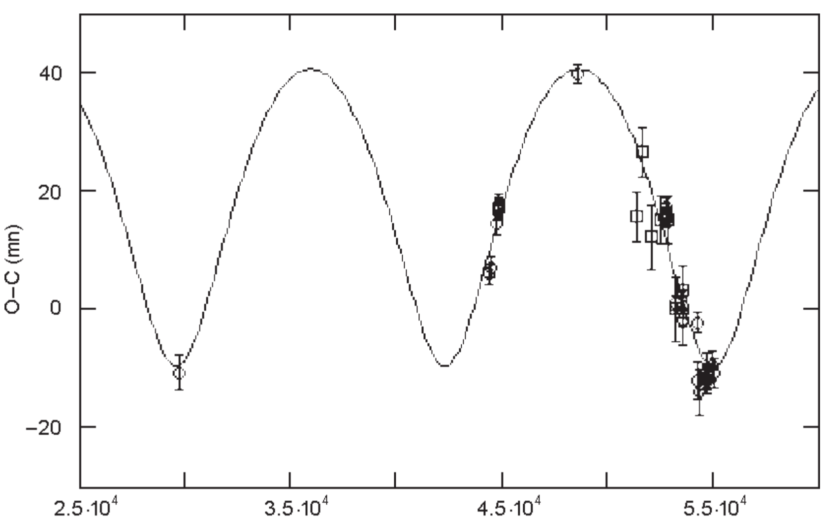

Figure 5. O–C diagram (1940–2009) for VZ Lib with the light-travel time calculation, after several iterations. Note than the error bars are much smaller than in Figure 4 which was for iteration 0.

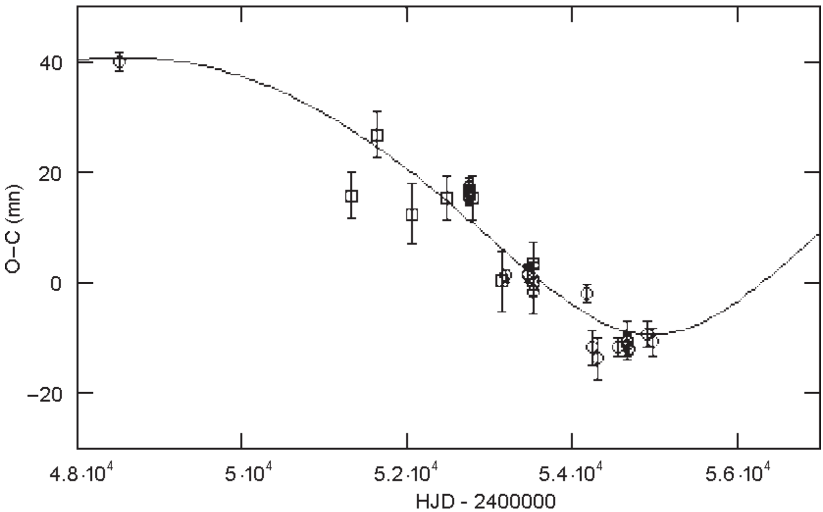

Figure 6. O–C diagram (1991–2009) for VZ Lib. A close-up of Figure 5.

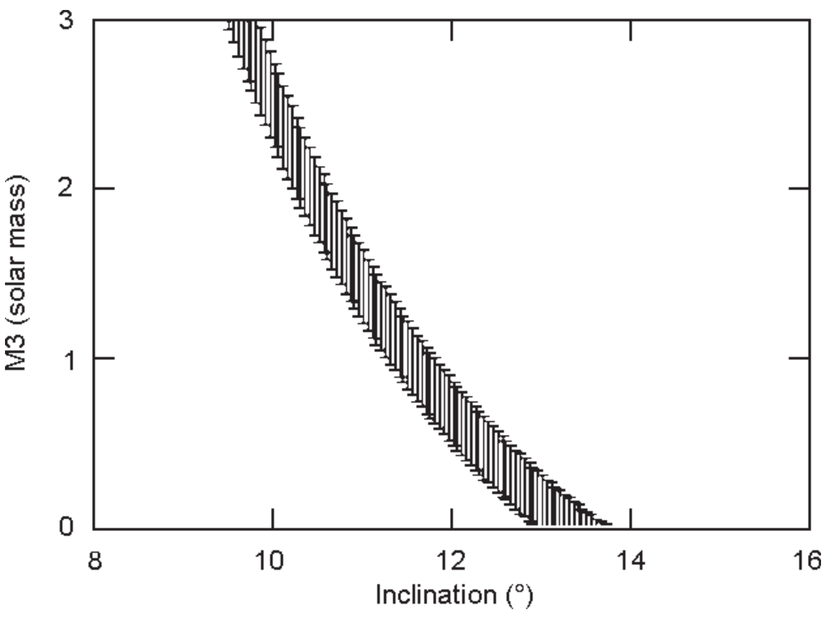

Figure 7. The mass of the third star as a function of the inclination.